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A HALF-WAVE AUTO-TRANSFORMER MAGNETIC AMPLIFIER

9 January 1953

U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

A HALF-WAVE AUTO-TRANSFORMER MAGNETIC AMPLIFIER

Prepared by:

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ABSTRACT: Herein is described a half-wave bridge
magnetic amplifier utilizing auto-transformation
directly on the reactor cores for supplying output
voltages in the order of line voltage or higher.
Other design considerations applicable to all half-
wave bridge magnetic amplifiers are discussed.

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This is a report of circuitry developed in connection with
the 60 cycle magnetic control amplifier phase under broad
program NOL-Re4a-78-2-53.

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                          Commander

                          D. S. MUZZEY, Jr.
                          By direction

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ILLUSTRATIONS

A HALF-WAVE AUTO-TRANSFORMER MAGNETIC AMPLIFIER

INTRODUCTION

1. Magnetic amplifiers for servomechanisms and other control devices often must possess rapid speed of response. The minimization of the delay in such magnetic amplifiers by the use of the half-wave circuit has been discussed by Messrs. Lufcy, Schmid, and Barnhart[1] of the Naval Ordnance Laboratory. This and other advantages strongly indicate the use of the half-wave bridge circuit for certain types of servo problems. The following discussion concerns itself with certain design considerations involved in the application of this basic type circuit.

2. The bridge circuit operating directly across the line voltage cannot produce an output voltage much more than about 50% of line rms. One possible solution to the problem of higher output voltages when such are needed is herein suggested. By this method, higher output voltages can be obtained without the addition of an external transformer.

OUTPUT VOLTAGE LEVEL

3. The output voltage of a half-wave bridge magnetic amplifier is a series of unidirectional pulses with a peak level somewhat lower than line voltage. Their amplitude is determined by the relation of the amplifier's internal impedance to the load impedance. The maximum possible output, a complete half-wave of voltage measured in rms volts, would be 0.707 of the rms value of a full sine wave with the same peak value. This maximum value will be reduced by the internal drop in the amplifier to some value, possibly 70% of the maximum possible, or about 0.5 of line voltage rms. As can be seen, the conventional half-wave bridge magnetic amplifier is well adapted to driving motors demanding less than line voltage, such as the 24 volt and 57.5 volt motors.

4. The occasion may arise, however, when it is necessary to drive a motor of full line voltage rating, at nearly full rated torque while at the same time retaining the advantages of the half-wave bridge circuit. Such a problem was assigned to this Division recently. A 115 volt 2 phase motor was required to drive a large frictional load consisting of two Model A helipots at a gear ratio of 1:12 from the motor. This required almost full rated output torque of the motor specified. Other considerations demanded the fast speed of response of a half-wave circuit. In the solution of this problem, a novel circuit was designed that provided the above features.

5.   Figure 1 will be recognized as the conventional half-wave bridge magnetic amplifier employing DC reference circuits. When the output voltage of this circuit is insufficient to meet the requirements, several possibilities present themselves. First, the rms value of the output voltage can be increased by making the system full-wave, although it becomes extremely difficult to obtain the one cycle speed of response inherent in the half-wave system. Also, use of full-wave circuitry necessitates the doubling in number of all major components, i.e., cores and rectifiers, and the subsequent increase in amplifier bulk and weight. Another possibility is to place a transformer across the line and operate the bridge at a higher voltage level as shown in figure 2. A simplification of this circuit with the center tapped transformer supplying two legs of the bridge is shown in figure 3. This approach to the problem of supplying higher voltages is widely used in conventional full-wave circuitry[2]. Both of these circuits, however, require the addition of an external transformer, which is subject to high losses in supplying half-wave current.

6.   It is possible to supply the higher voltages required without the additional transformer by the use of auto-transformation directly on the reactor cores. This circuit is shown in figure 4. With no signal, the cores are referenced to fire at some predetermined firing angle by the reference circuit as in the conventional half-wave bridge. On the conducting or saturating half-cycle, auto-transformation occurs before the cores reach saturation. After saturation, there is no more transformation, but quiescent current flows down the sides of the bridge. Under both conditions, however, the bridge remains balanced. With a control signal the cores are preset during the control half-cycle of the line voltage to fire at different points on the conducting half-cycle. Again before saturation of either core, the transformation takes place in both, but the bridge is balanced. When one core saturates ahead of the other under signal conditions, the bridge is unbalanced. Assume in figure 4 that core 1 has saturated while core 2 remains unsaturated. Assume also that the saturated impedance of core 1 has gone to zero. The circuit then becomes the circuit of figure 5(A). Winding No. 2 contributes little due to the direction of the rectifiers except that the polarity of voltage is such as to oppose current by-passing the load through winding No. 2. The load is seen to be across the line stepped-up by the auto-transformer of winding No. 1 as shown in figure 5(B). As in the conventional circuit, the bridge is rebalanced after core 2 saturates.

7.   The advantage of this circuit is evident. The output voltages are of a higher level than those supplied by the half-wave bridge operating directly off the line. It is possible by using two such circuits in a full-wave configuration to reach and exceed line rms voltage. Curves comparing the output voltages of these two types of half-wave bridge are shown in

figure 6. The load in both cases was a 115 volt 2 phase
Diehl Motor, type FPE 25-53-2.

8. In addition to supplying higher output voltages without
the addition of an external transformer, the auto-transformer
circuit has maintained the one cycle speed of response inher-
ent in the half-wave circuit. This is shown in figure 7 where
the lower trace is the half-wave rectified control current into
the stage and the upper trace is the half-wave output current
into a resistive load. Complete response is obtained in the
next half-cycle after control signal is applied.

9. Figure 8 gives the details of construction of the half-
wave auto-transformer bridge magnetic amplifier having the
gain curves shown in figure 6. The output voltage obtained
is not simply a function of the step-up turns ratio alone.
Other factors that determine this output voltage are the forward
impedance of the rectifiers and the DC resistance of the bridge
windings. The forward impedance of the rectifiers prevents
full line voltage appearing across the common windings of the
auto-transformer windings and thus reduces the step-up. The
series windings needed for the auto-transformers also add
additional copper resistance to the power windings and reduce
the actual output voltage. Variations in gain and amplifier
size are realizable by proper design. The following circuit
considerations pertinent to the design of this amplifier in
most cases apply to all half-wave bridge magnetic amplifiers.

RECTIFIER REQUIREMENTS

10. The choice of rectifier plate size is dictated by the
current level in the bridge. This is simple enough and except
for the necessity of keeping forward impedance at a minimum,
there is no restriction on size except to maintain sufficient
area to prevent heating. It is generally advisable from life
and packaging considerations to so rate the rectifiers that
at maximum anticipated ambient temperature, the spot tempera-
tures of the rectifiers do not exceed the manufacturer's
maximum ratings.

11. The question of the proper number of rectifier plates to
use is more involved. To choose the number of plates necessary
to absorb line voltage is to ignore several important factors
at work in the magnetic amplifier. The first of these is the
fact that on the half-cycle when the rectifier blocks current
flow and the cores are unsaturated, the reference circuit
windings induce into the power windings voltages in opposition
to line voltage. This causes the core impedance to appear high
and thus part of the line voltage appears on the cores instead
of on the reverse resistance of the rectifiers. The actual
measured reverse voltage on a rectifier may be so low as to
warrant use of only one plate even when operating from a 115
volt line. This would seem to indicate a low number of recti-
fier plates. However, an additional fact which must be

3

considered is the requirement that a high reverse resistance
be maintained to insure high gain. The impedance offered to
the control circuit during the control half-cycle, if low,
tends to load the signal source down in its effort to change
the flux in the core and reduces the gain. If the reverse
resistance of the rectifiers is low, this detrimental condition
results. The cores, however, are generally referenced to some
predetermined point of firing by a current flow during the
control half-cycle. In order to accomplish this action with
a minimum of loading of the control circuit, the reference
winding turns are kept low so that impedances in the reference
circuit when reflected into the control circuit by the square
of the turns ratio will appear high. To allow the core to be
referenced by low reverse resistance in the rectifiers or by
shunted rectifiers is to effectively use a reference winding
of the number of turns of the power windings and thereby reflect
low impedances into the control circuit. Hence, the choice of
the number of rectifier plates to be used is dictated by the
requirements of maintaining a high enough reverse resistance
to achieve the desired gain without raising the forward impe-
dance of the rectifiers to the point where the power delivered
to the load is lowered.

CORE REQUIREMENTS

12. The reactor core acts as a variable impedance possessing
high impedance in its unsaturated state and going to a low
impedance when saturation takes place. Control is exercised
during the non-saturating half-cycle and output power is delivered
when the core goes into saturation. By reducing the internal
impedance of the amplifier, a higher gain is achieved. Although
this is beneficial for gain, it also results in higher quiescent
currents. These currents, with no signal, are conducted down
the sides of the bridge after the cores saturate. When the
internal or saturated impedance of the amplifier is reduced
to an extremely low value, the currents often reach the point
where the attendant heating in the cores is beyond the practical
limit. One approach to this problem has been the use of line
resistors. By placing a power resistor in the line circuit
feeding the bridge, the quiescent currents in the legs of the
bridge are reduced. However, the line resistor does not greatly
affect the gain of the bridge. Before either core fires, only
magnetizing currents flow in this resistor so there is very
little voltage drop and almost full line voltage appears on
the cores. Under signal conditions and after one core fires,
the load current flows through this resistor causing a drop
and reducing the voltage on the second core. The second core
fires later than it would have without the line resistor, and
it can be shown that the average voltage across the load, and
thus the gain, is virtually unchanged. Use of the line resis-
tor results in a distribution of heat between the cores and
the resistor. In many cases this is an acceptable method of
controlling quiescent currents. However, there are occasions
when the total heat dissipation in the circuit is unallowable.

Also, mounting and packaging problems arise from the use of a power resistor of the wattage usually required.

13. In an effort to avoid the disadvantages of the line resistors in controlling quiescent currents, another approach to the problem has been investigated. An attempt was made to increase the inductive reactance of the cores by redesigning the core configuration and copper-iron ratio. This would achieve restriction of quiescent current by a wattless element. It was found, however, that the rectangular core material* used had a saturated inductance very small compared to the resistance of the windings. The quiescent current was determined mainly by the winding resistance plus the forward resistance of the rectifiers. Quiescent currents then can be controlled by proper selection of winding resistance, but as was mentioned before, an increase in winding resistance results in a loss in gain.

14. For the actual determination of the windings to go on the auto-transformer, it is best to begin with a conventional half-wave bridge designed for operation from a 115 volt line. This represents the power windings between the taps in figure 4 and corresponding points on the opposite legs. To this conventional bridge are added the series windings necessary for the desired step-up. allowance being made for the loss of primary voltage in the forward resistance of the rectifiers. If the total winding resistance has not risen to an objectional value, the circuit will now operate satisfactory. If the winding resistance has been increased too much by the addition of the series windings of the auto-transformer, adjustment can be made by increasing the wire size. Additional rectifier plates are necessary with the auto-transformer in accordance with the discussion in paragraph 11.

15. It has been apparent that the variables of gain, maximum voltage output, amplifier size and heating are interdependent. With the preceding considerations in mind, the typical amplifier circuit of figure 8 may be amended to meet the desired specifications.

---

* Orthonol 3

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   E. A. Gaugler, United States Patent 2,569,468, Method of Producing Grain Oriented Ferro-Magnetic Alloys, Issued Oct. 2, 1951 (Application filed June 16, 1948).
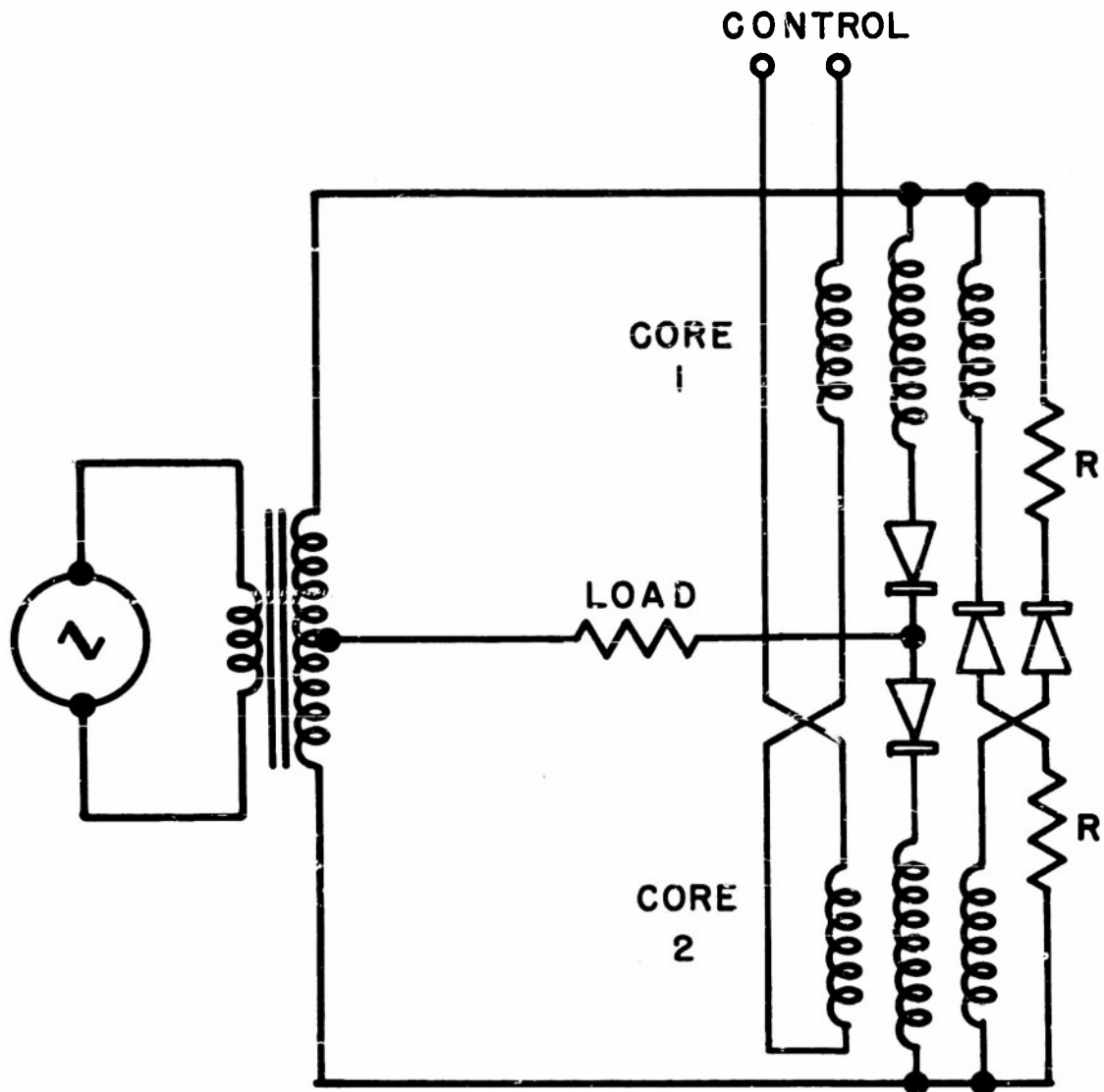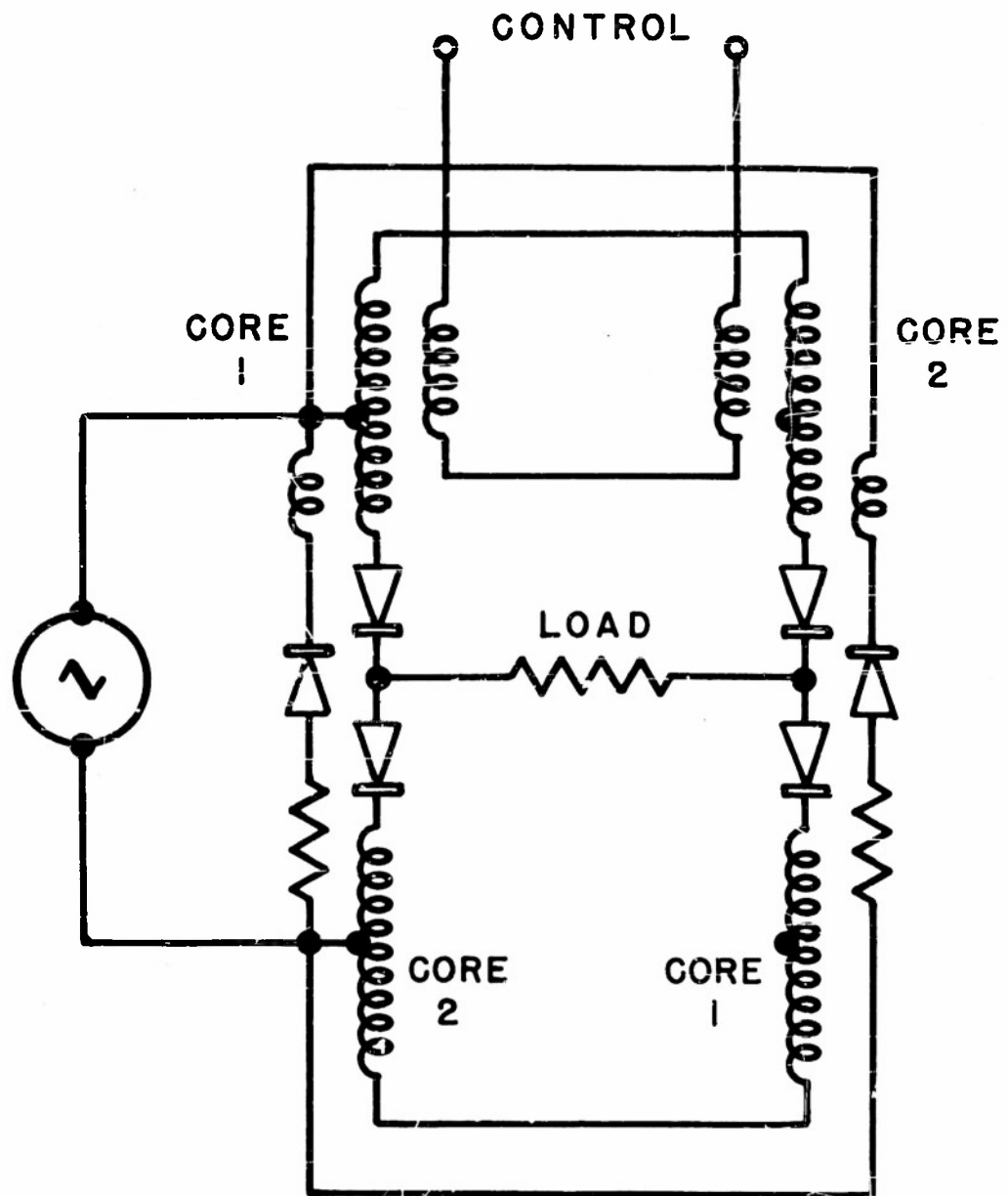
FIGURE I

7

FIGURE 2

8
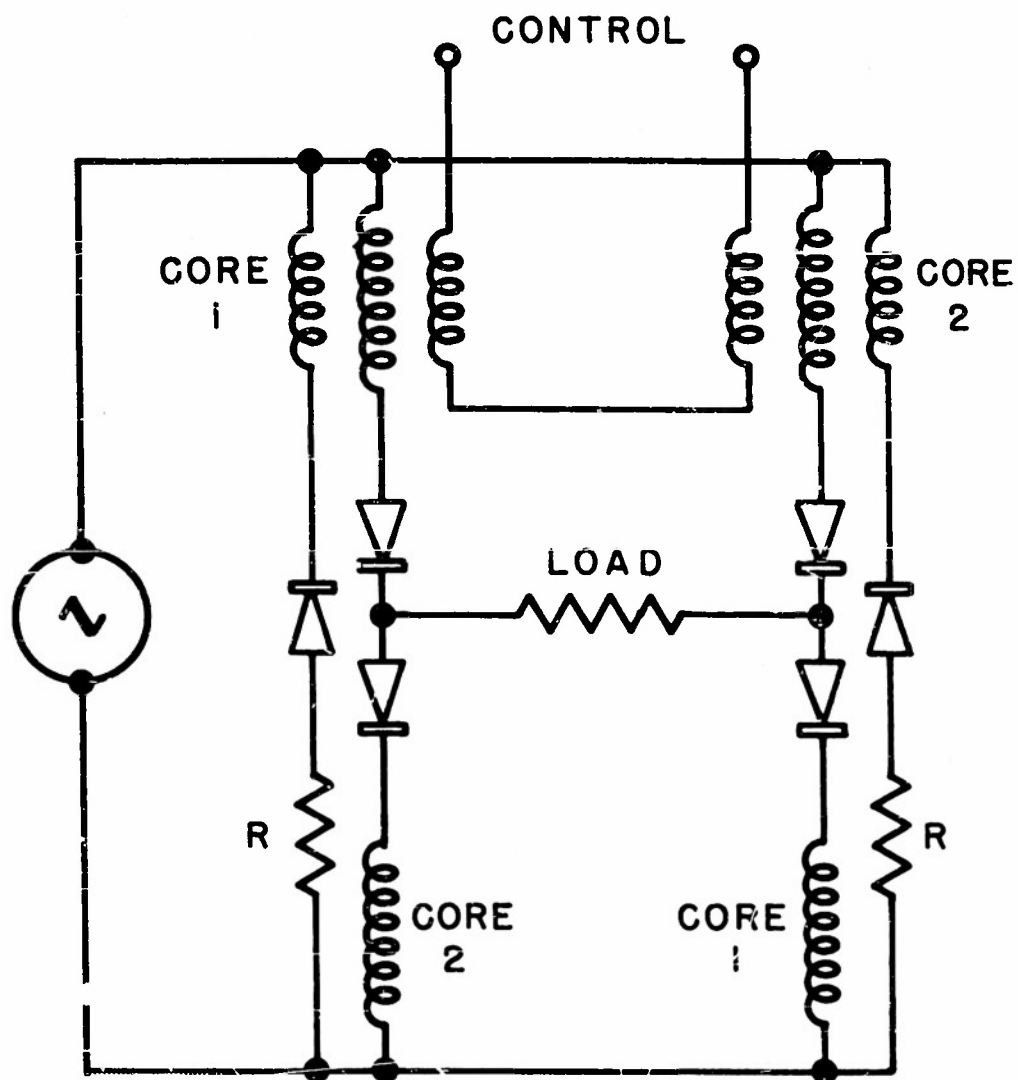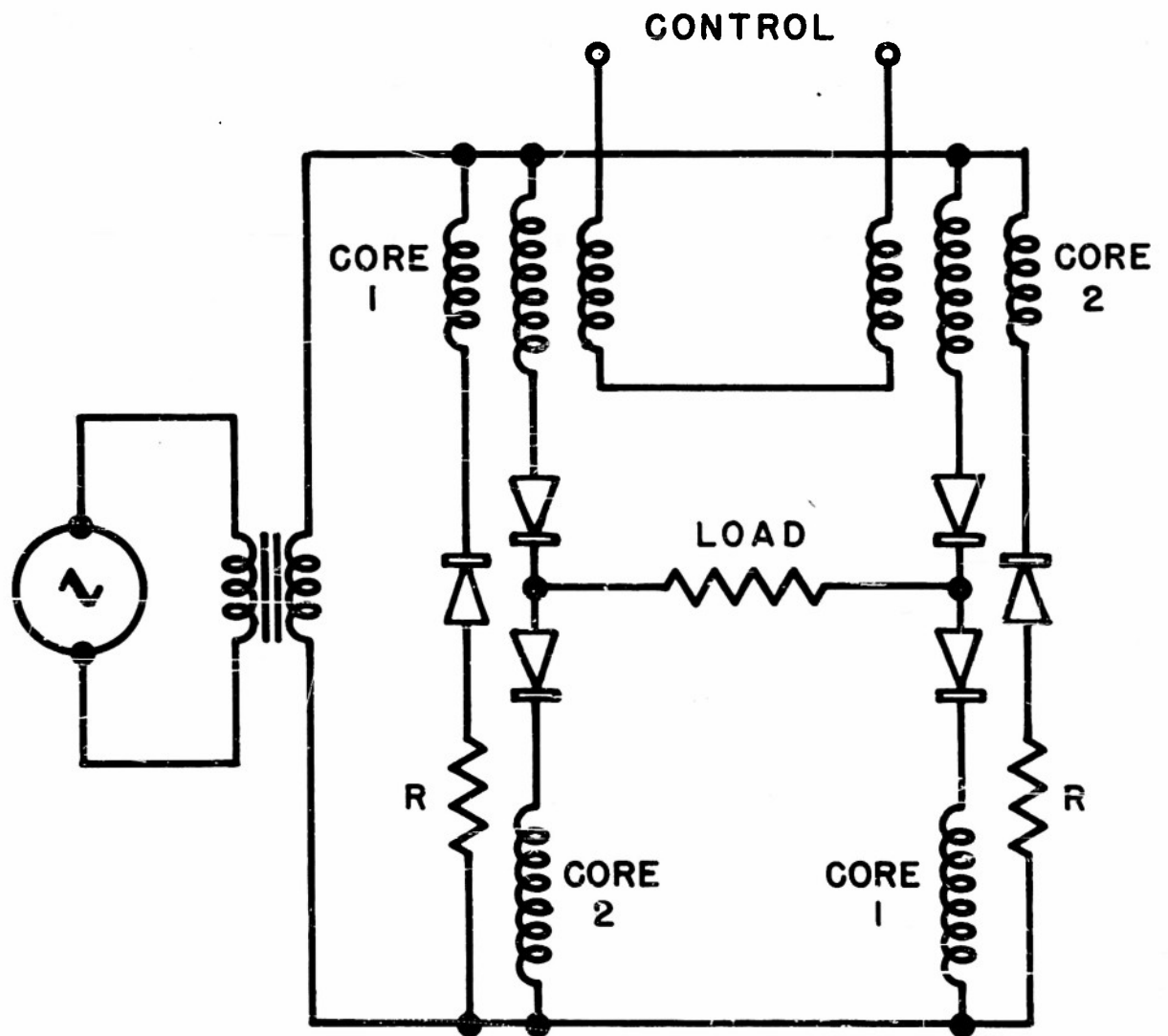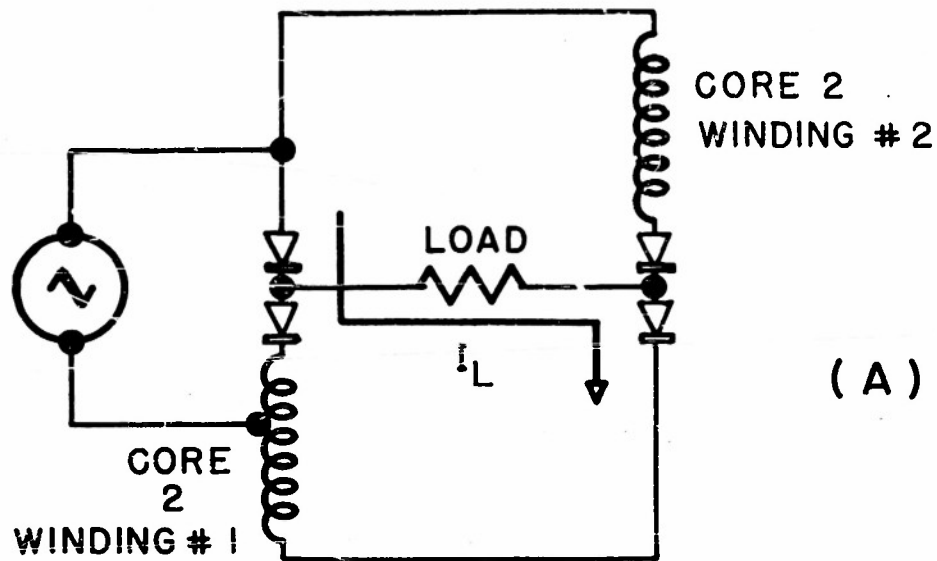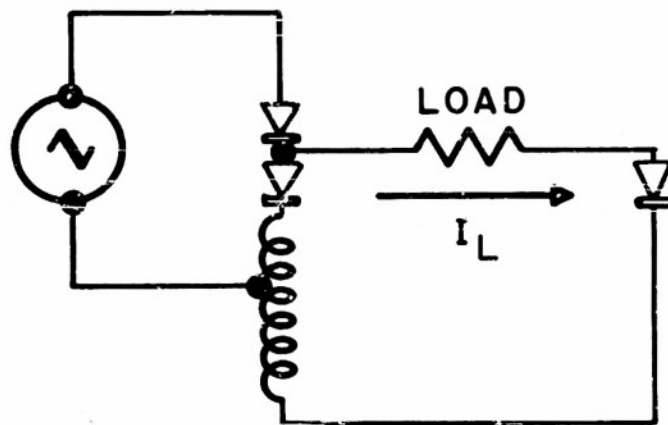
FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

FIGURE 7

CONTROL

CORE 1

CORE 2

200#33   100#33   100#33   3000#30   200#33

1400#30/600#30

115 V.
60
~

6 PLATES
1/2" SQ.

6 PLATES
1" SQ.

6 PLATES
1" SQ.

LOAD

6 PLATES
1" SQ.

6 PLATES
1" SQ.

6 PLATES
1/2" SQ.
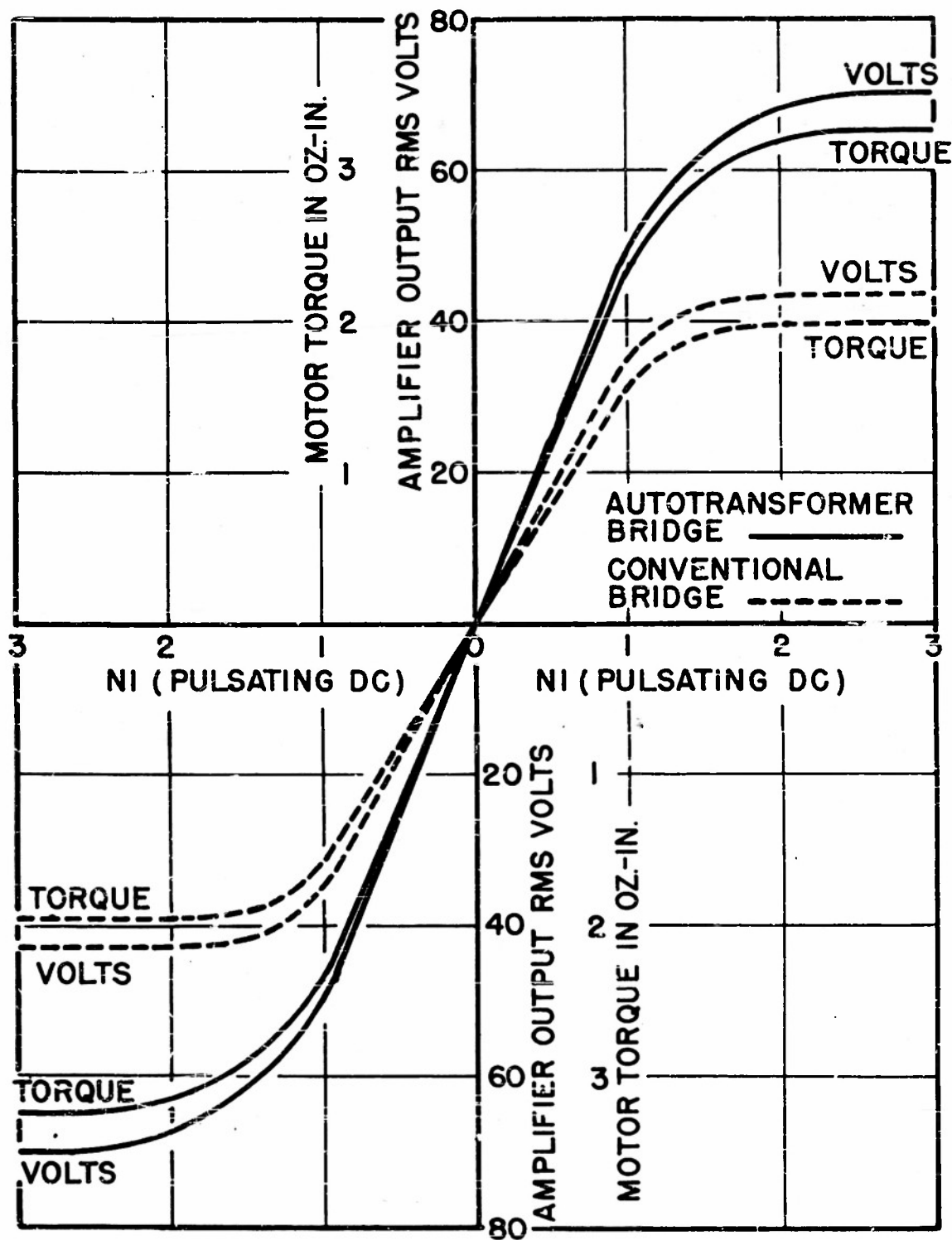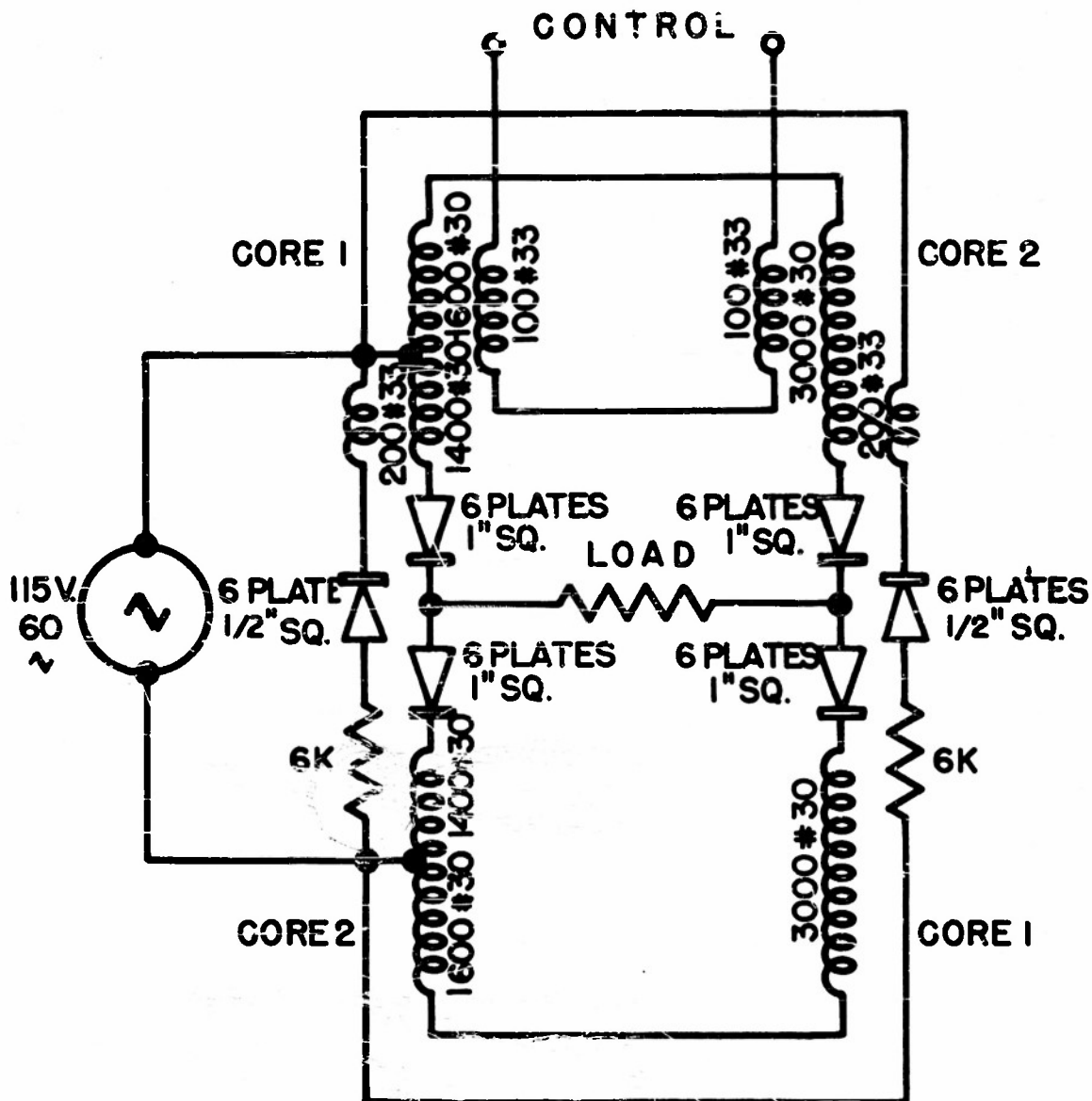
6K

6K

CORE 2

1600#30 1400#30

3000#30

3000#30

CORE 1

CORE CONSTRUCTION
TAPE WOUND TOROID
INSIDE DIAMETER $1\frac{1}{2}$"
OUTSIDE DIAMETER 2"
WIDTH 1"
TAPE THICKNESS 0.002"
CORE AREA 1.4 CM^2

FIGURE 8

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